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**Observation of the Semileptonic Decay  $D^0 \rightarrow a(0)(980)^- e^+ \nu(e)$  and Evidence for  $D^+ \rightarrow a(0)(980)^0 e^+ \nu(e)$**

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# Observation of the Semileptonic Decay $D^0 \rightarrow a_0(980)^- e^+ \nu_e$ and Evidence for $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$

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Using an  $e^+e^-$  collision data sample of  $2.93 \text{ fb}^{-1}$  collected at a center-of-mass energy of  $3.773 \text{ GeV}$  by the BESIII detector at BEPCII, we report the observation of  $D^0 \rightarrow a_0(980)^- e^+ \nu_e$  and evidence for  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$  with significances of  $6.4\sigma$  and  $2.9\sigma$ , respectively. The absolute branching fractions are determined to be  $\mathcal{B}(D^0 \rightarrow a_0(980)^- e^+ \nu_e) \times \mathcal{B}(a_0(980)^- \rightarrow \eta \pi^-) = [1.33_{-0.29}^{+0.33}(\text{stat}) \pm 0.09(\text{syst})] \times 10^{-4}$  and  $\mathcal{B}(D^+ \rightarrow a_0(980)^0 e^+ \nu_e) \times \mathcal{B}(a_0(980)^0 \rightarrow \eta \pi^0) = [1.66_{-0.66}^{+0.81}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$ . This is the first time the  $a_0(980)$  meson has been measured in a  $D^0$  semileptonic decay, which would open one more interesting page in the investigation of the nature of the puzzling  $a_0(980)$  states.

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The study of the nature of the light scalar resonances  $a_0(980)$  and  $f_0(980)$  has long been one of the central problems of nonperturbative QCD, as they are important for understanding the way that chiral symmetry is realized in the low-energy region and, consequently, for understanding confinement physics [1], i.e., the main consequences of QCD in the hadron world [2,3]. The constituent quark model treats the lightest scalar resonances  $a_0(980)/f_0(980)$  as conventional  $q\bar{q}$  states [4]. However, the structure of these states seems to be more complicated, and they have also been identified with a compact diquark-antidiquark state or a  $K\bar{K}$  bound state [5,6], considering that the simple  $q\bar{q}$  picture encounters serious difficulties in understanding the mass problem of the light scalar mesons as well as the  $a_0(980)$  production in the radiative decay of  $\phi \rightarrow \gamma a_0(980)$ , which turn out to be readily resolved in the tetraquark scenario [7]. On the other hand, a few tetraquark candidates have been recently observed by various experiments [8–10], but these new states have all heavy-heavy quark contents.

The transition of  $D \rightarrow a_0(980)$  can be naturally decomposed from the lepton pairs in the  $c \rightarrow d e^+ \nu_e$  decay, in which final-state interaction is avoided, and only the spectator light quark is related in the formation of the  $a_0(980)$ . Therefore, of great interest is to search for the  $D^0 \rightarrow a_0(980)^- e^+ \nu_e$  and  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$ , which will provide the information about the  $a_0^-(a_0^+) = d\bar{u}(u\bar{d})$  and  $a_0^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$  components in the corresponding  $a_0(980)$  wave functions due to its clear production mechanism [11]. Furthermore, the experimental search for  $D \rightarrow a_0(980) e^+ \nu_e$  will be crucial to understand the decay dynamics of  $D$  mesons.

In this Letter, we present the first observation of the semileptonic decay  $D^0 \rightarrow a_0(980)^- e^+ \nu_e$  and evidence for  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$ . The data sample used in this analysis was collected at center-of-mass energy  $\sqrt{s} = 3.773 \text{ GeV}$  [near the nominal mass of the  $\psi(3770)$ ] by the BESIII detector at the BEPCII collider and corresponds to an integrated luminosity of  $2.93 \text{ fb}^{-1}$  [12].

The BESIII detector is described in detail elsewhere [13]. The detector has a geometrical acceptance of 93% of  $4\pi$ . It includes a multilayer drift chamber (MDC) for measuring the momenta and specific ionization energy loss ( $dE/dx$ ) of charged particles, a time-of-flight (TOF) system which contributes to charged particle identification (PID), a CsI(Tl) electromagnetic calorimeter (EMC) for detecting

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electromagnetic showers, and a muon chamber system designed for muon identification.

A detailed GEANT4-based [14] Monte Carlo (MC) simulation of the BESIII detector is used to determine the detection efficiencies and evaluate the possible background sources. Events are generated by the generator KKMC [15] using EVTGEN [16], with the effects of the beam energy spread and initial-state radiation (ISR) being taken into account. Final-state radiation is treated via the PHOTOS package [17].

A double-tag analysis technique [18] is employed; this takes advantage of  $D$  mesons produced via exclusive  $D\bar{D}$  pair production in the decay of the  $\psi(3770)$  resonance. We reconstruct  $\bar{D}$  mesons using specific hadronic decays, producing a sample of single-tag (ST) events. We then search these ST events for the partner  $D$  meson undergoing the decay process of interest; successful searches result in our sample of double-tag (DT) events. This strategy suppresses non- $D\bar{D}$  background effectively and provides a measurement of absolute branching fractions independent of the integrated luminosity and the  $D\bar{D}$  production cross section. These absolute branching fractions are calculated as

$$\mathcal{B}_{\text{sig}} = \frac{N_{\text{sig}}^{\text{obs}}}{\sum_{\alpha} N_{\text{tag}}^{\text{obs},\alpha} \epsilon_{\text{tag,sig}}^{\alpha} / \epsilon_{\text{tag}}^{\alpha}}, \quad (1)$$

in which  $\alpha$  denotes the different ST modes,  $N_{\text{tag}}^{\text{obs},\alpha}$  is the ST yield for tag mode  $\alpha$ ,  $N_{\text{sig}}^{\text{obs}}$  is the sum of the DT yields from all ST modes, and  $\epsilon_{\text{tag}}^{\alpha}$  and  $\epsilon_{\text{tag,sig}}^{\alpha}$  refer to the corresponding ST efficiency and the DT efficiency for the ST mode  $\alpha$  determined by MC simulations. In this approach, most of the systematic uncertainties arising from the ST reconstruction are canceled.

The ST  $\bar{D}$  mesons are reconstructed with the following final states:  $\bar{D}^0 \rightarrow K^+\pi^-$ ,  $K^+\pi^-\pi^0$ ,  $K^+\pi^-\pi^+\pi^-$ , and  $D^- \rightarrow K^+\pi^-\pi^-$ ,  $K^+\pi^-\pi^-\pi^0$ ,  $K_S^0\pi^-$ ,  $K_S^0\pi^-\pi^0$ ,  $K_S^0\pi^+\pi^-\pi^-$ ,  $K^+K^-\pi^-$ . The charged particles  $K^{\pm}$  and  $\pi^{\pm}$ , as well as the neutral particles  $\pi^0$  and  $K_S^0$ , are selected with the same criteria as those in Ref. [19]. Throughout this Letter, charge-conjugate modes are implied.

Two key kinematic variables, the energy difference  $\Delta E \equiv E_D - E_{\text{beam}}$  and beam-constrained mass  $M_{\text{BC}} \equiv \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_D|^2/c^2}$  are used to identify the ST  $\bar{D}$  candidates. Here,  $E_{\text{beam}}$  is the beam energy, and  $E_D$  and  $\vec{p}_D$  are the reconstructed energy and momentum of the  $\bar{D}$  candidate in the  $e^+e^-$  center-of-mass system. For true  $\bar{D}$  candidates,  $\Delta E$  and  $M_{\text{BC}}$  will peak at zero and the nominal mass of the  $D$  meson, respectively. We accept the  $\bar{D}$  candidates with  $M_{\text{BC}}$  greater than 1.83  $\text{GeV}/c^2$  and apply mode-dependent  $\Delta E$  requirements of approximately 3 standard deviations. When multiple candidates exist, at most one candidate per tag mode per charm (i.e.,  $D$  or  $\bar{D}$ ) is retained in each event by selecting the candidate with the

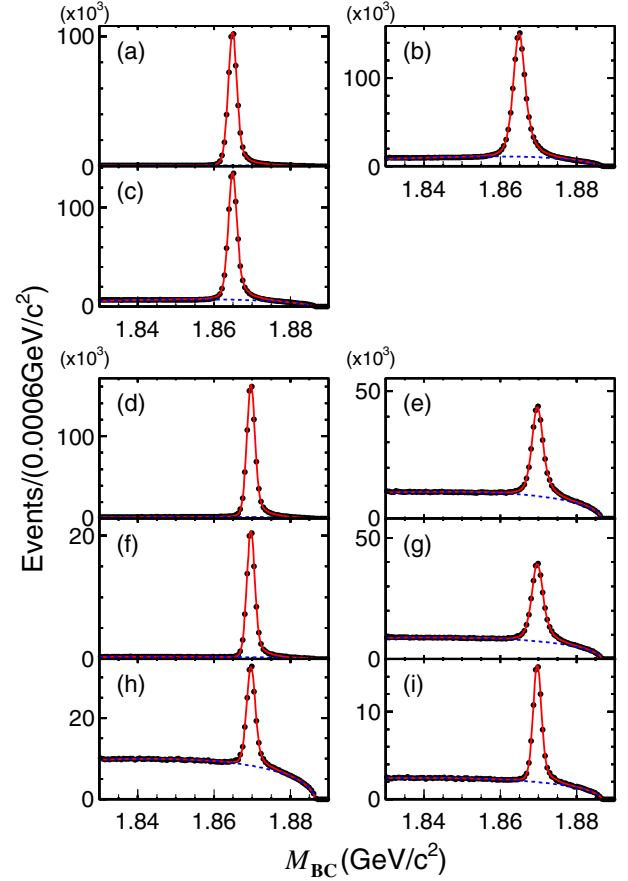


FIG. 1. Fits to the  $M_{\text{BC}}$  distributions of the ST candidates. The first two rows show the  $\bar{D}^0$  modes (a)  $K^+\pi^-$ , (b)  $K^+\pi^-\pi^0$ , (c)  $K^+\pi^-\pi^+\pi^-$ , and the last three rows show the  $D^-$  modes (d)  $K^+\pi^-\pi^-$ , (e)  $K^+\pi^-\pi^-\pi^0$ , (f)  $K_S^0\pi^-$ , (g)  $K_S^0\pi^-\pi^0$ , (h)  $K_S^0\pi^+\pi^-\pi^-$ , (i)  $K^+K^-\pi^-$ . Points with error bars represent data, the (red) solid lines are the total fits, and the (blue) dashed lines represent the background contributions.

smallest  $|\Delta E|$  [20]. The ST yields are determined by performing a maximum likelihood fit to the  $M_{\text{BC}}$  distributions of the accepted  $\bar{D}$  candidates, as shown in Fig. 1. The signal shape is modeled by the MC simulated shape convolved with a Gaussian function with free parameters. The MC simulation includes the effects of beam energy spread, ISR, the  $\psi(3770)$  line shape, and experimental resolution, while the Gaussian convolution allows for small imperfections in the MC simulation. The combinatorial background is modeled by an ARGUS function [21]. The ST yield for each mode is calculated by subtracting the integrated combinatorial background yield from the total number of events contained in the signal regions defined as  $1.858 < M_{\text{BC}} < 1.874 \text{ GeV}/c^2$  for  $\bar{D}^0$  and  $1.860 < M_{\text{BC}} < 1.880 \text{ GeV}/c^2$  for  $D^-$ . The ST yields in the data and the corresponding ST efficiencies are listed in Table I.

We search in the selected ST events for the semileptonic decays  $D^0 \rightarrow a_0(980)^- e^+ \nu_e$  and  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$  using the remaining charged tracks and photon candidates

TABLE I. ST yields in data  $N_{\text{tag}}^{\text{obs},\alpha}$ , ST efficiencies  $\epsilon_{\text{tag}}^\alpha$ , and DT efficiencies  $\epsilon_{\text{tag},\text{sig}}^\alpha$ , with statistical uncertainties, for each mode  $\alpha$ . Branching fractions of  $K_S^0 \rightarrow \pi^+\pi^-$ ,  $\pi^0 \rightarrow \gamma\gamma$ , and  $\eta \rightarrow \gamma\gamma$  are not included in the efficiencies. The first three rows are for  $\bar{D}^0$  candidates, and the last six rows are for  $D^-$  candidates.

Mode	$N_{\text{tag}}^{\text{obs},\alpha}$	$\epsilon_{\text{tag}}^\alpha$ (%)	$\epsilon_{\text{tag},\text{sig}}^\alpha$ (%)
$K^+\pi^-$	$541541 \pm 753$	$65.92 \pm 0.02$	$15.18 \pm 0.20$
$K^+\pi^-\pi^0$	$1040340 \pm 1209$	$34.66 \pm 0.01$	$8.00 \pm 0.08$
$K^+\pi^-\pi^+\pi^-$	$706179 \pm 982$	$38.96 \pm 0.01$	$7.02 \pm 0.09$
$K^+\pi^-\pi^-$	$806444 \pm 953$	$51.08 \pm 0.02$	$5.23 \pm 0.07$
$K^+\pi^-\pi^-\pi^0$	$252088 \pm 816$	$25.91 \pm 0.02$	$2.40 \pm 0.06$
$K_S^0\pi^-$	$100019 \pm 337$	$54.33 \pm 0.05$	$5.55 \pm 0.21$
$K_S^0\pi^-\pi^0$	$235011 \pm 759$	$29.63 \pm 0.03$	$3.10 \pm 0.08$
$K_S^0\pi^+\pi^-\pi^-$	$131815 \pm 710$	$32.49 \pm 0.05$	$2.66 \pm 0.10$
$K^+K^-\pi^-$	$69642 \pm 398$	$40.58 \pm 0.06$	$4.09 \pm 0.20$

not used for the ST candidate. Here, the  $a_0(980)^-$  and  $a_0(980)^0$  are reconstructed by their prominent decays to  $\eta\pi^-$  and  $\eta\pi^0$ , respectively. The PID of the charged hadrons (positrons) is accomplished by combining the  $dE/dx$  and TOF ( $dE/dx$ , TOF, and EMC) information to construct a likelihood  $\mathcal{L}_i$  ( $\mathcal{L}'_i$ ) for each of the hypotheses  $i = e/\pi/K$ . The charged pion candidate is required to satisfy  $\mathcal{L}_\pi > \mathcal{L}_K$  and  $\mathcal{L}_\pi > 0.1\%$ . The positron candidate is required to satisfy  $(\mathcal{L}'_e/\mathcal{L}'_e + \mathcal{L}'_\pi + \mathcal{L}'_K) > 0.8$  and  $E/(pc) > 0.8$ , where  $E$  is the energy deposited in the EMC, and  $p$  is the momentum measured by the MDC. A candidate signal event is required to have a single positron (electron) for signal  $D$  ( $\bar{D}$ ) decays. The  $\pi^0$  and  $\eta$  candidates are formed from pairs of photon candidates with invariant two-photon masses within (0.115, 0.150) and (0.508, 0.572) GeV/ $c^2$ , respectively. To improve the kinematic resolution, a one-constraint (1-C) kinematic fit is performed by constraining the  $\gamma\gamma$  invariant mass to the expected nominal mass [22]. Background from wrong-pairing photons is suppressed by requiring the decay angle defined as  $|\cos\theta_{\text{decay},\pi^0(\eta)}| = (|E_{\gamma 1} - E_{\gamma 2}|/|\vec{p}_{\pi^0(\eta)}|)$  to be less than 0.80 and 0.95 for the  $\pi^0$  and  $\eta$  candidates, respectively. Here,  $E_{\gamma 1}$  and  $E_{\gamma 2}$  are the energies of the two daughter photons of the  $\pi^0(\eta)$ , and  $\vec{p}_{\pi^0(\eta)}$  is the reconstructed momentum of the  $\pi^0(\eta)$ . The photon energies and  $\vec{p}_{\pi^0(\eta)}$  are the results of the kinematic fit. The  $a_0(980)^-$  candidate is formed with a charged pion and a selected  $\eta$  candidate. The  $a_0(980)^0$  candidate is formed from the combination of  $\pi^0$  and  $\eta$  candidates with the least  $\chi^2_{\text{1C},\pi^0} + \chi^2_{\text{1C},\eta}$ , where  $\chi^2_{\text{1C},\pi^0}$  and  $\chi^2_{\text{1C},\eta}$  are the  $\chi^2$  values of the 1-C kinematic fits of the  $\pi^0$  and  $\eta$  candidates, respectively. Furthermore, any event with extra unused charged tracks or  $\pi^0$  candidates are rejected. This  $\pi^0$  veto suppresses the following backgrounds:  $D^0 \rightarrow \rho^- e^+ \nu_e$  and  $D^0 \rightarrow K^*(892)^- e^+ \nu_e$  [with  $K^*(892)^- \rightarrow K_S^0 \pi^-$ ] for the

$D^0 \rightarrow a_0(980)^- e^+ \nu_e$  mode;  $D^+ \rightarrow K_S^0 e^+ \nu_e$  and  $D^+ \rightarrow \bar{K}^*(892)^0 e^+ \nu_e$  [with  $\bar{K}^*(892)^0 \rightarrow K_S^0 \pi^0$ ] for  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$ . In all cases here,  $K_S^0 \rightarrow \pi^0 \pi^0$ . Detailed MC studies show that  $D^{0(+)} \rightarrow K^*(892)^{-(0)} e^+ \nu_e$  followed by  $\bar{K}^* \rightarrow K_L^0 \pi$  are prominent backgrounds, where the  $K_L^0$  signal in the EMC can mimic the higher-energy daughter of the  $\eta$  candidate. To suppress these background, the lateral moment [23] of EMC showers, which peaks around 0.15 for real photons but varies from 0 to 0.85 for  $K_L^0$  candidates, is required to be within (0, 0.35) for the higher-energy photon from the  $\eta$  decay. This requirement suppresses about 70% of the  $K_L^0$  backgrounds, while retaining 95% of the signal, and ultimately leads to a limited  $K_L^0$  contribution and a negligible systematic uncertainty.

For the semileptonic signal candidate, the undetected neutrino is inferred by studying the variable  $U \equiv E_{\text{miss}} - c|\vec{p}_{\text{miss}}|$ , where  $E_{\text{miss}}$  and  $\vec{p}_{\text{miss}}$  are the missing energy and momentum carried by the neutrino from the semileptonic decay. These are calculated as  $E_{\text{miss}} = E_{\text{beam}} - E_{a_0(980)} - E_e$  and  $\vec{p}_{\text{miss}} = -(\vec{p}_{\text{tag}} + \vec{p}_{a_0(980)} + \vec{p}_e)$ , respectively, where  $E_{a_0(980)}$  ( $E_e$ ) and  $\vec{p}_{a_0(980)}$  ( $\vec{p}_e$ ) are the energy and momentum of  $a_0(980)$  (positron), and  $\vec{p}_{\text{tag}}$  is the momentum of the ST  $\bar{D}$  in the center-of-mass frame. We calculate  $\vec{p}_{\text{tag}} = \hat{p}_{\text{tag}} \sqrt{E_{\text{beam}}^2/c^2 - M_D^2}$ , where  $\hat{p}_{\text{tag}}$  is the unit vector in the momentum direction of the ST  $\bar{D}$  and  $M_D$  is the nominal  $D$  mass [22]. The signal candidates are expected to peak around zero in the  $U$  distribution and near the  $a_0(980)$  mass in the  $M_{\eta\pi}$  spectrum.

To obtain the signal yields, we perform two-dimensional (2D) unbinned maximum likelihood fits to the  $M_{\eta\pi}$  versus  $U$  distributions, combining all tag modes. Projections of the 2D fits are shown in Fig. 2. The signal shape in the  $U$  distribution is described by the MC simulation and that in the  $M_{\eta\pi}$  distribution is modeled with a usual Flatté formula [24] for the  $a_0(980)$  signal. The mass and two coupling constants  $g_{\eta\pi}^2$  and  $g_{K\bar{K}}^2$  are fixed to 0.990 GeV/ $c^2$ , 0.341 (GeV/ $c^2$ ) $^2$ , and 0.304 (GeV/ $c^2$ ) $^2$  [25], respectively. The backgrounds are divided into three classes: the residual background from semileptonic  $D \rightarrow \rho, K_S^0$  and  $K^*$  decays mentioned previously (bkg I), the partially reconstructed hadronic  $D$  decays (bkg II), and the non- $D\bar{D}$  background (bkg III). For each background source in bkg I, the shape and yield are determined by the MC simulation incorporating the corresponding branching fraction [22]. The shape and yield for bkg II are fixed based on the generic  $D\bar{D}$  MC sample, in which all particles decay inclusively based on the branching fractions taken from the PDG [22] but with bkg I modes removed. Bkg III from the continuum processes  $e^+e^- \rightarrow$  light quarks and  $\tau^+\tau^-$  is modeled with a MC-determined shape generated with a modified LUND model [26], with the yield determined in the fit. The 2D probability density functions (PDFs) of all these components are constructed by the product of the  $U$  and  $M_{\eta\pi}$

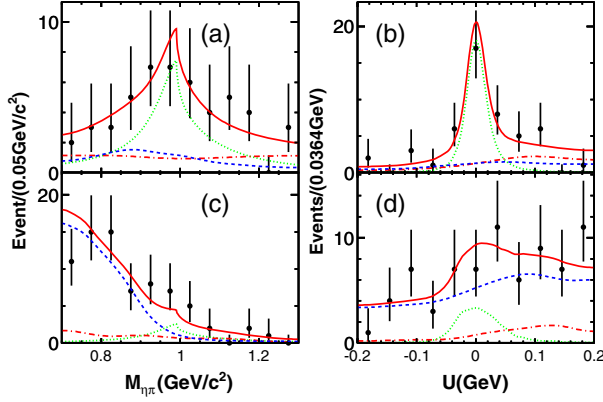


FIG. 2. Projections of the 2D fit on (left)  $M_{\eta\pi}$  and (right)  $U$  for (a),(b)  $D^0 \rightarrow a_0(980)^- e^+ \nu_e$  and (c),(d)  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$ . Points with error bars are data. The (red) solid curves are the overall fits, the (blue) dashed line denotes the sum of the bkg I and bkg II, the (red) dotted-dashed lines denote the bkg III, and the (green) dotted lines show the fitted signal shape.

distributions due to the negligible correlation between the two observables according to the exclusive background channel MC simulation.

The 2D fits yield  $25.7^{+6.4}_{-5.7}$  signal events for  $D^0 \rightarrow a_0(980)^- e^+ \nu_e$  and  $10.2^{+5.0}_{-4.1}$  signal events for  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$ . The statistical significance of the signal taken to be  $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\text{best}})}$ , where  $\mathcal{L}_{\text{best}}$  and  $\mathcal{L}_0$  are the maximum likelihood values with the signal yield left free and fixed at zero, respectively, is  $6.5\sigma$  for  $D^0 \rightarrow a_0(980)^- e^+ \nu_e$  and  $3.0\sigma$  for  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$ . The corresponding DT efficiencies are presented in Table I.

The systematic uncertainties in the measurements are summarized in Table II and discussed below. The uncertainty due to the ST  $\bar{D}$  meson largely cancel in the DT analysis method. The uncertainties associated with the tracking and PID for the charged pion are estimated to be 1.0% and 0.5%, respectively, by investigating a control sample  $D^+ \rightarrow K^- \pi^+ \pi^+$  based on a partial reconstruction technique. Similarly, the uncertainty related with the  $\pi^0$  reconstruction, including the detection of two photons, is found to be 1.0% by studying the control sample  $D^0 \rightarrow K^- \pi^+ \pi^0$ . Since  $\eta$  candidates are reconstructed similarly, the corresponding uncertainty is also assigned to be 1.0%. The uncertainties related to tracking and PID for the positron are investigated with a radiative Bhabha control sample in the different polar angle and momentum bins. The values for the tracking and PID are 1.0% and 0.6%, respectively, obtained after reweighting according to the distributions of momentum and polar angle of the positron from the signal MC sample. Considering the similar selection criteria of  $\eta$  and  $\pi^0$ , the uncertainty arising from the choice of the best  $\eta\pi^0$  combination in the  $D^+$  decay is studied with a di- $\pi^0$  sample of DT  $D$  hadronic decay,  $D^0 \rightarrow K^- \pi^+ \pi^0$  versus  $\bar{D}^0 \rightarrow K^+ \pi^- \pi^0$  and is taken as 0.3% [27].

TABLE II. The relative systematic uncertainties (in %) on the branching fraction measurements. Items marked with \* are derived from the fit procedure and are not used when evaluating the upper limit of the branching fraction.

Source	$D^0 \rightarrow a_0(980)^- e^+ \nu_e$	$D^+ \rightarrow a_0(980)^0 e^+ \nu_e$
Tracking	2.0	1.0
$\pi$ PID	0.5	...
$\pi^0$ reconstruction	...	1.0
$\eta$ reconstruction	1.0	1.0
Positron PID	0.6	0.6
The best $\eta\pi^0$ combination	...	0.3
Lateral moment requirement	1.6	1.6
Form factor model	5.3	5.6
$\eta$ and $\pi^0$ branching fraction	0.5	0.5
MC statistics	0.6	0.9
* $U$ resolution	2.7	1.1
* $a_0(980)$ line shape	0.2	0.3
*Background modeling	0.3	2.0
Total	6.7	6.6

The efficiency of the lateral moment requirement for photons is studied in different energy and polar angle bins using a control sample of radiative Bhabha events. The average data MC efficiency difference after reweighting according to the energy and polar angle distributions of the signal MC sample is taken as the systematic uncertainty. The form factor of the semileptonic decay for the nominal signal MC sample is parametrized with the model of Ref. [28]. An alternative MC sample based on the Isgur-Scora-Grinstein-Wise (ISGW2) model [29] is produced; the change in the detection efficiency is assigned as the uncertainty associated with the signal model. The uncertainties in the branching fractions of submodes are taken from the current world averages [22]. The effect of limited MC statistics is also included as a systematic effect. Uncertainties associated with the 2D fits are estimated by varying the signal and background shapes and certain background contributions in bkg I and bkg II within their uncertainties. For the resolution of  $U$ , the distribution in  $U$  of the  $D^0$  decay is convolved with a Gaussian function with free parameters and the fit is redone. Considering the limited statistics and large background contributions, the width of the Gaussian function for the  $D^+$  decay is fixed to be  $(\text{FWHM}_+/\text{FWHM}_0)\sigma_0$ , in which  $\sigma_0$  is the output Gaussian width in the fit to the  $D^0$  case, and  $\text{FWHM}_+$  and  $\text{FWHM}_0$  are the full width at half maximum of the nominal  $U$  shape for the  $D^+$  and  $D^0$  signal MC samples, respectively. Changes in the signal yields are assigned to be the corresponding uncertainties. For the  $a_0(980)$  line shape,



the mass and the two coupling constants in the Flatté formula are varied by 1 standard deviation, and the average change in the signal yield is taken to be the relevant uncertainty. The shapes of the  $D\bar{D}$  and non- $D\bar{D}$  backgrounds are modeled using the kernel PDF estimator [30] based on the MC samples with a smoothing parameter set to 1.5. The uncertainties of the shapes are determined by changing the smoothing parameter by  $\pm 0.5$ , and we take the relative changes on the signal yield as the associated uncertainties. We also shift the yields of bkg I and bkg II in the fits by  $1\sigma$  calculated from the corresponding branching fractions, luminosity measurements [12], and  $D\bar{D}$  cross section [31]. The average changes on the signal yields are taken as the corresponding uncertainties.

Because of the limited statistical significance of the  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$  mode, an upper limit on the signal yield is also computed using a Bayesian method. The fit likelihood as a function of the number of signal events denoted as  $f_{\mathcal{L}}(N)$  is convolved with Gaussian functions that represent the systematic uncertainties. For all uncertainty sources not from the 2D fit, the effects are modeled by Gaussian functions having widths equal to the corresponding uncertainties. Uncertainties due to the fit procedure are computed using the toy MC simulated events sampled according to the shape of the data. In each toy experiment, we perform a nominal fit and one alternative fit with the shape parameters varied as described above. A Gaussian function is obtained with parameters taken from the mean and the root-mean-square of the resultant discrepancy between the two fitted yields. By integrating up to 90% of the physical region for the smeared  $f_{\mathcal{L}}(N)$ , we obtain an upper limit of  $N^{\text{up}} < 18.5$  at the 90% confidence level (C.L.) for the  $D^+ \rightarrow a_0(980)^0 e^+ \nu_e$  yield.

Since the branching fraction of  $a_0(980) \rightarrow \eta\pi$  has not been well measured, we report the product branching fractions, obtaining

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow a_0(980)^- e^+ \nu_e) \times \mathcal{B}(a_0(980)^- \rightarrow \eta\pi^-) \\ = (1.33_{-0.29}^{+0.33} \pm 0.09) \times 10^{-4}, \\ \mathcal{B}(D^+ \rightarrow a_0(980)^0 e^+ \nu_e) \times \mathcal{B}(a_0(980)^0 \rightarrow \eta\pi^0) \\ = (1.66_{-0.66}^{+0.81} \pm 0.11) \times 10^{-4}, \end{aligned}$$

where the first (second) uncertainties are statistical (systematic). The upper limit on the product branching fraction for  $D^+$  decay is determined as  $\mathcal{B}(D^+ \rightarrow a_0(980)^0 e^+ \nu_e) \times \mathcal{B}(a_0(980)^0 \rightarrow \eta\pi^0) < 3.0 \times 10^{-4}$  at the 90% C.L. By convolving the likelihood value from the nominal fits with Gaussian functions whose widths represent the systematic uncertainties for the  $D^0$  and  $D^+$  decays, we calculate the signal significance including systematic uncertainties to be  $6.4\sigma$  and  $2.9\sigma$  for the  $D^0$  and  $D^+$  decays, respectively.

To summarize, we present the observation of the semileptonic decay of  $D^0 \rightarrow a_0(980)^- e^+ \nu_e$  and the evidence for

$D^+ \rightarrow a_0(980)^0 e^+ \nu_e$ . The measured branching fractions are over  $2\sigma$  deviated from the calculated values based on the QCD light-cone sum rule [32]. Taking the lifetimes of  $D^0$  and  $D^+$  [22] into consideration and assuming that  $\mathcal{B}(a_0(980)^- \rightarrow \eta\pi^-) = \mathcal{B}(a_0(980)^0 \rightarrow \eta\pi^0)$ , we find a ratio of partial widths of

$$\frac{\Gamma(D^0 \rightarrow a_0(980)^- e^+ \nu_e)}{\Gamma(D^+ \rightarrow a_0(980)^0 e^+ \nu_e)} = 2.03 \pm 0.95 \pm 0.06,$$

consistent with the prediction of isospin symmetry, where the shared systematic uncertainties have been canceled. This is the first time the  $a_0(980)$  meson has been measured in a  $D^0$  semileptonic decay. Discovery of the  $a_0(980)$  in the theoretically clean  $D^0$  semileptonic decay would open one more interesting page in the investigation of the nontrivial nature of the  $a_0(980)$  states. Form factor analysis of a future experiment with higher statistics can better uncover the inner structure of  $a_0(980)$ . Along with the result of the branching fraction of  $D^+ \rightarrow f_0 e^+ \nu_e$ , a result in preparation at BESIII, we will have valuable input for understanding the nature of the light scalar mesons [33].

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